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PRELIMINARY PERFORMANCE OF A LOW LOADING HIGH TIP SPEED FAN STAGE

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ABSTRACT

Limited data indicates the feasibility of designing fan stages for operation with weak oblique shocks in the rotor blade tip region. A 488 m/sec (1600 ft/sec) rotor tip speed fan indicated an overall efficiency of 0.846 at a pressure ratio of 1.51 even though the rotor blades had incurred damage in the leading edge tip region prior to obtaining the design speed performance. After the test it was observed that a number of the rotor blade mid-span dampers had failed, subsequently damaging a number of rotor blades in the leading edge tip region.

INTRODUCTION

Studies of blade-element data for the tip sections of high tip speed, transonic, axial-flow compressor rotor blade rows show that minimum losses occur when the passage shock is oblique. For these high pressure ratio designs, the hub section was matched to operate at minimum loss when the tip section was operating with a normal shock in the passage. To realize maximum efficiency, the hub section should be designed to operate at minimum loss when the tip operates with oblique shocks. This type design for high tip speeds should produce high efficiency at a moderate pressure ratio. Furthermore, it would be expected to have a large stall margin and relatively good distortion tolerance. Furthermore, the forward projected wave pattern should be minimized and therefore, shock or multiple pure tone noise may be minimized.

A transonic fan stage was designed and fabricated by AirResearch Mfg. Co. under NASA contract NAS 3-13498 for the purpose of evaluating these concepts. During the shake-down test on August 17, 1971, a mechanical failure of the rotor blades was encountered. The outer portions of five of the mid-span vibration dampers broke off and resulted in fairly extensive damage to the blade tip leading edge regions of 23 of the 40 rotor blades. During the shake-down test but prior to the discovery of the failure, a limited amount of aerodynamic data was recorded.

This report presents a summary of the limited performance obtainable from this data. It is important to note that since it was impossible to establish the exact time of the resulting blade damage, this data was probably obtained with varying amounts of rotor blade damage present. However, the performance results presented herein are considered of significance since they strongly indicate that the design objective of relatively high efficiency and large stall margin were achieved.

APPARATUS AND PROCEDURE

General Design Concepts

The design values of basic parameters for the subject stage are:

Rotor tip speed	488 m/sec (1600 ft/sec)
Stage pressure ratio	1.5
Flow per unit inlet annulus area	205 kg/(sec)(m^2) (42 lb/(sec)(ft^2))
Hub-tip ratio (rotor inlet)	0.5
Rotor blade tip solidity	1.6
Rotor blade aspect ratio	2.76
Stator blade aspect ratio	3

The high rotor tip speed and specific flow requirements result in a design which has supersonic inlet velocities relative to the rotor blade over about 83 percent of the inlet passage height. For axial velocity ratios of the order of one, only a small amount of turning is necessary in the rotor tip region to meet the total pressure ratio requirements. Thus the rotor discharge relative velocities are supersonic over the outer 30 percent of the rotor exit passage. To meet the condition of supersonic inlet and outlet relative velocities with minimum losses, this outer portion of the rotor blade was designed for operation with weak oblique passage shockes as illustrated in figure 1. As shown in figure 1, one oblique shock is generated off the leading edge of one blade and is cancelled on the suction surface of the adjacent blade. A second oblique shock emanates from the trailing edge and is cancelled on the pressure surface of the adjacent blade.

The hub region of the rotor blade operates with subsonic relative velocities at the inlet and the discharge and a more conventional circular arc blade shape is utilized. The other blade elements are designed in such a way as to achieve a smooth fairing between the blade shapes at the hub and tip. Portions of this region of the blade will, of course, operate with stronger oblique shocks and portions with normal shocks, however, the relative Mach numbers at the lower radii where the stronger shock system exists are low enough that the associated losses are not large.

Mechanical design considerations indicated the necessity for rotor blade mid-span dampers. These were located about mid-chord of the blade surfaces and approximately 30 percent of span from the tip.

The rotor discharge absolute Mach numbers and flow angles are not large, with a maximum angle of 37° and corresponding Mach number of 0.81. Thus, the stators were designed as conventional circular arc vanes.

For the design criteria listed above and the selected rotor inlet tip diameter of 0.73 m (28.74 in.), the resultant design flow was 67.1 kg/sec (147.9 lb/sec). Based on the design input losses, the computed overall stage efficiency was 0.861.

Test Facility

The basic test facility has an atmospheric inlet and atmospheric discharge. Air is brought into the cell through filters and enters the compressor or fan through a bellmouth followed by a constant area duct. The air is discharged from the compressor or fan through concentric collectors and out through two exhaust ducts each of which contains flow measuring orifices and throttle valves. Power to drive the compressor or fan is supplied by a hot gas turbine. Fan speed and the throttle valves are manually controlled.

Instrumentation

The instrumentation used for this test was similar to that shown in reference 1. Inlet total pressure was measured using pitot rakes in the bellmouth ahead of the inlet duct. Inlet temperature was obtained from thermocouples on the debris screen covering the bellmouth. Stage discharge total pressures were obtained from wake rakes which spanned the stator vane gaps at each of nine radial positions. Stage discharge temperature were obtained from five rakes located circumferentially so as to effectively span a stator vane gap. Each rake had shielded thermocouples at nine radial positions. Wall static pressures were measured over the rotor tip region and at other strategic locations throughout the vehicle. High frequency pressure transducers were also installed over the rotor tip region. Radial traverses of pressures and temperature were also made at the rotor inlet and discharge and at the stator discharge. Air flow was measured through sharp edge orifices in the exhaust ducts down stream of the

compressor rig. Output from the fixed performance type instrumentation is fed directly to the computer and that from the radial traverses and high frequency pressure transducers is recorded on magnetic tape. The data which goes directly to the computer is continuously processed, recorded, and displayed on cathode-ray tubes with an update each 30 seconds. This data can be recalled and printed on demand. For identification purposes this data is referred to as time scan data.

RESULTS AND DISCUSSION

A partial map of the overall fan stage performance is shown in figure 2. Most of the information shown in figure 2 was selected from the time scan data. One data point, identified in figure 2 as reading 16, was a complete stabilized point where data from all instrumentation was recorded. Even though the time scan data may be obtained during transient operation, it is considered indicative of the performance of the fan as all changes in throttle valve setting and speed were made slowly.

The fan achieved design pressure ratio at a flow about 2 percent above design with an efficiency only $1\frac{1}{2}$ points less than design. Because of the probable blade damage, the indicated efficiency is a conservative estimate of the efficiency potential of such a stage. At design speed the fan had a flow range of over 6 percent with the stall pressure ratio shown at 1.67. Because the range of the outlet pressure transducers was exceeded for the outer elements of the stage, the achieved stall pressure ratio is estimated to be on the order of 1.7. Thus, the stage exhibited a substantial pressure ratio range between design and stall.

The radial distribution of stage element performance for reading 16 is shown in figure 3. The presence of the mid-span damper at 30 percent span from the tip is noticeable in all the plots. The blade sections near the hub are not producing the desired pressure ratio and indicates a substantial efficiency decrement near the end wall. This region is operating with energy inputs less than design and with somewhat greater than design losses.

The radial distributions of the rotor inlet and discharge relative Mach numbers for reading 16 are shown in figure 4. From these it is clear that the rotor tip is operating with the prescribed supersonic discharge relative Mach numbers. The existence of supersonic relative discharge velocities indicate either weak oblique shocks or strong shocks followed by a substantial acceleration. With the indicated efficiency values in the tip region it appears highly unlikely that strong shock patterns could be present. The casing static pressures over the rotor tip are in agreement with this evaluation, i.e., the rotor for the condition near design is operating with only weak oblique shocks in the tip region.

For some operating conditions, relatively high vibratory stress levels were noted. It is felt that these stresses generated heavy loadings of the mid-span dampers and caused five to fail. The leading edge damage probably was a result of strikes by the pieces of dampers which were missing on inspection. The blade vibrations and damper failures are being investigated.

CONCLUDING REMARKS

A limited amount of data has indicated that it is feasible to design a fan for 488 m/sec (1600 ft/sec) rotor tip speed and a pressure ratio of 1.5 with an overall efficiency in the 0.85 range. It also appears that such a fan can be expected to exhibit a reasonable operating range. These results are sufficiently encouraging to warrant further evaluations of the principles involved in this stage design.

REFERENCE

1. Koch, C. C.; Bilwakesh, K. R.; and Doyle, V. L.: Evaluation of Range and Distortion Tolerance for High Mach Number Transonic Fan Stages. Vol. I. Rep. GE-R71-AEG-133, vol. 1, General Electric Co. (NASA CR-72806), Aug. 1971.

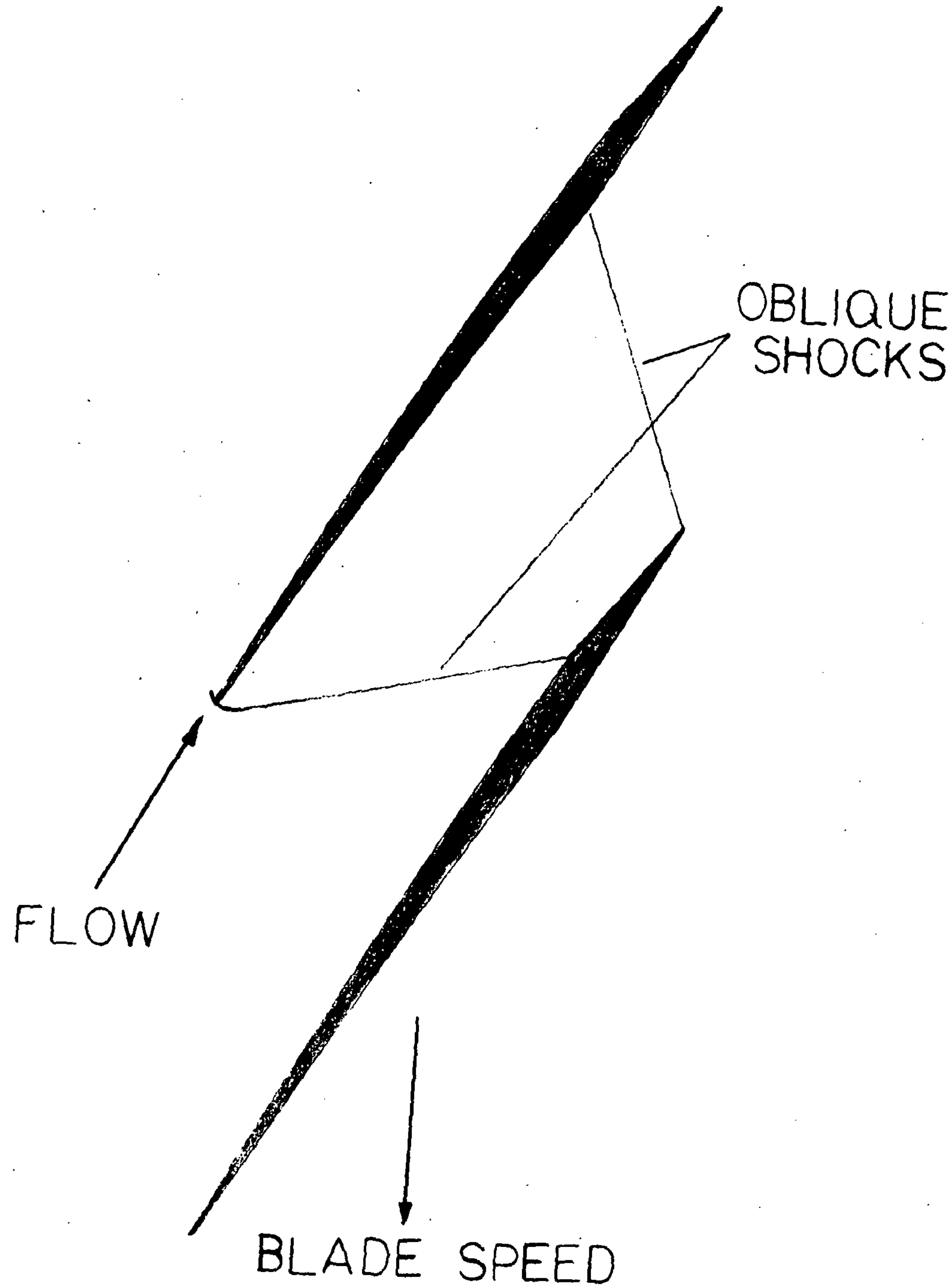

FIGURE 1. SCHEMATIC OF ROTOR BLADE TIP

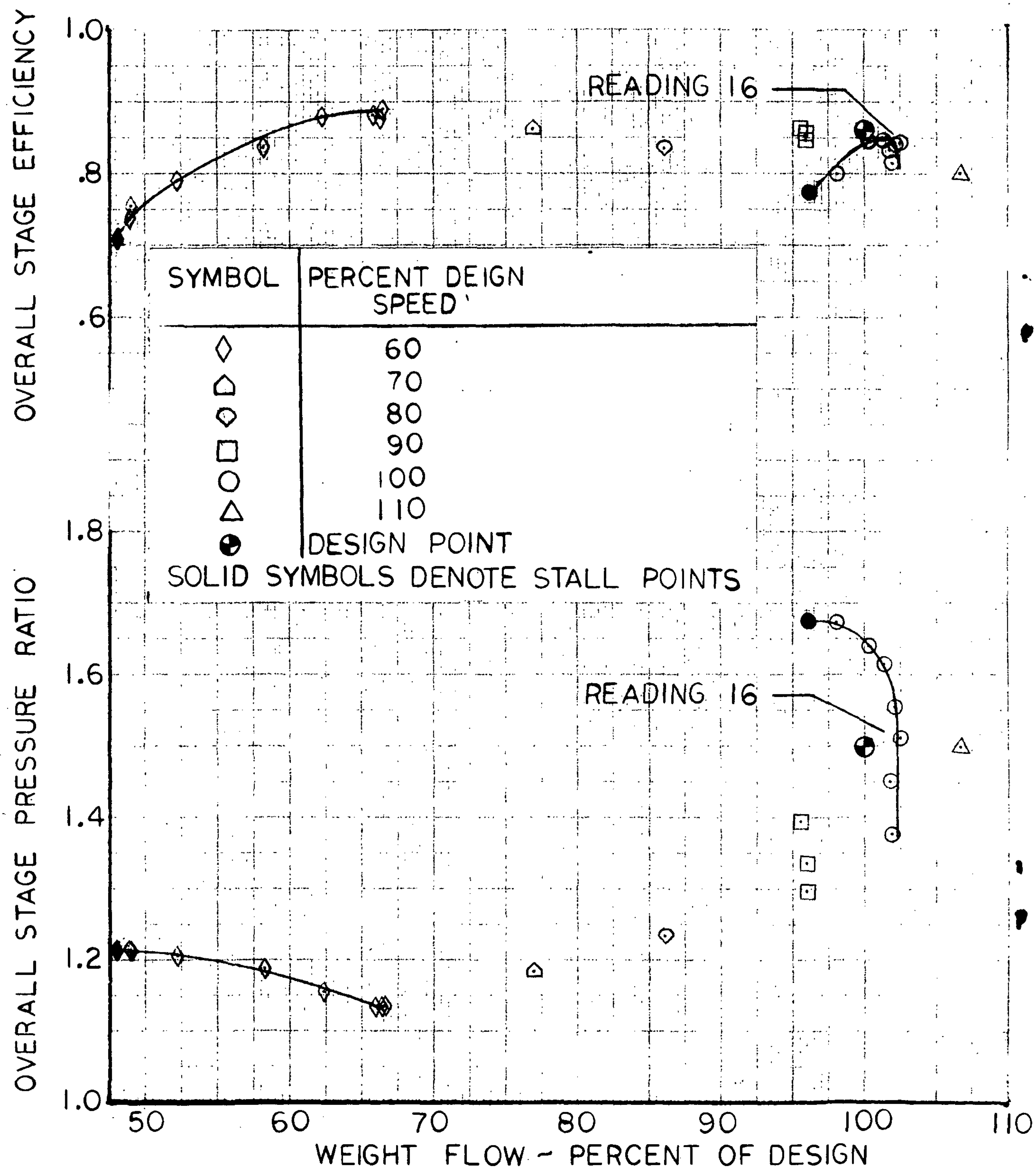

FIGURE 2. STAGE OVERALL PERFORMANCE

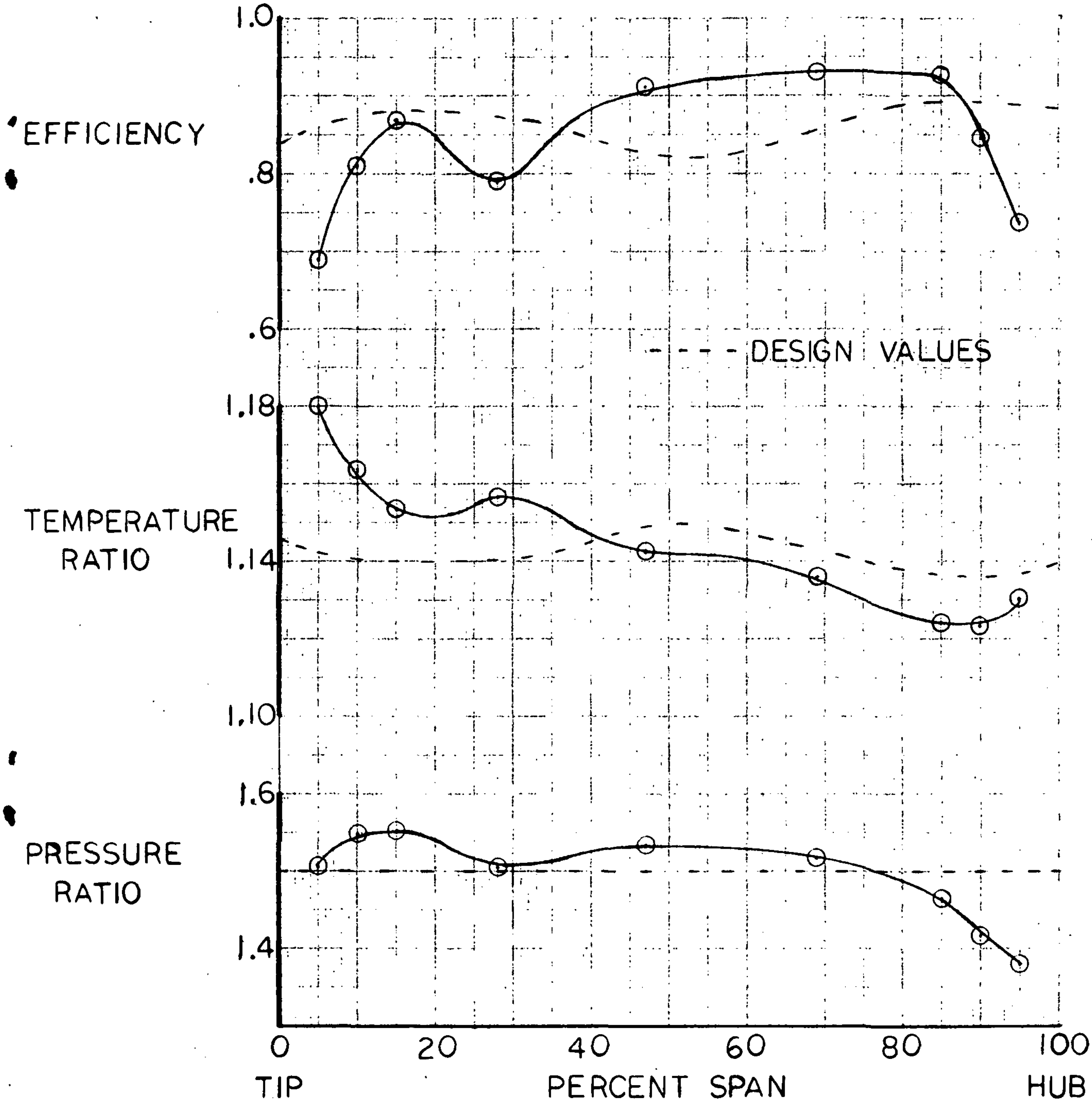

FIGURE 3. STAGE ELEMENT PERFORMANCE

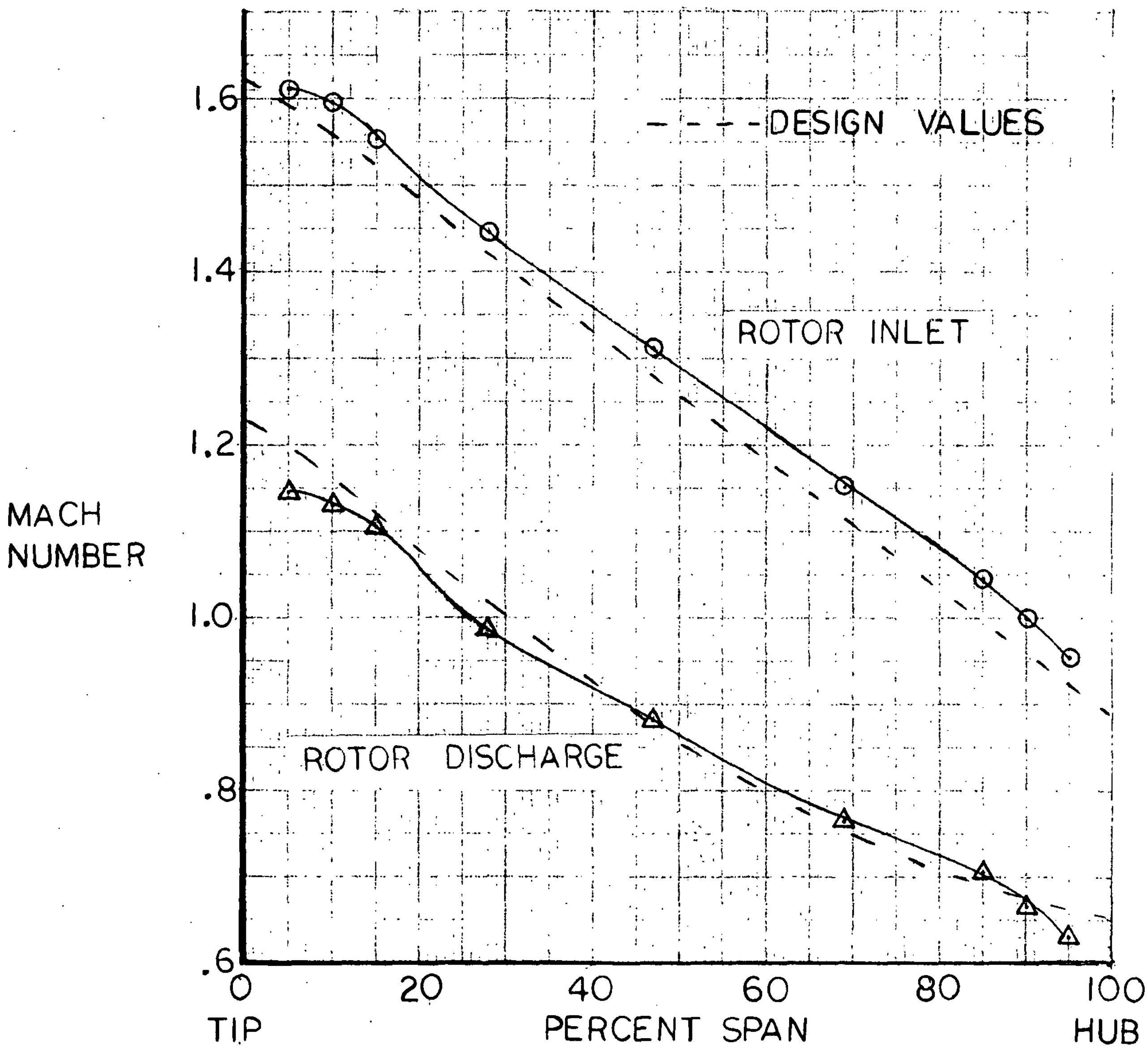

FIGURE 4. DISTRIBUTION OF ROTOR RELATIVE MACH NUMBERS